THE UNIVERSITY OF ALBERTA

NETWORK ANALYSER ACCURACY

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

by

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MARCH 31, 1960

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "NETWORK ANALYSER ACCURACY" submitted by MALCOLM McKITTRICK CHASE COLLINS in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The Contraves Network Analyser of the Department of Electrical Engineering at the University of Alberta has been in use for approximately two and one half years and during that time several problems concerning accuracy have arisen leaving the users uncertain as to the accuracy of the results of their studies. The main doubt concerns the losses measured for load flow studies.

Because of the prevailing uncertainties the author has undertaken a detailed study of the Network Analyser including a sample load flow study with a tabulation of the losses in the sample system. This study of the Analyser forms the basis for the conclusions and recommendations of this thesis.

With the aid of the conclusions and recommendations of this thesis the Network Analyser user may determine the losses in a system on which a load flow study is being done within useable accuracy limits.

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CHAPTER I

INTRODUCTION

In 1957 a Contraves Network Analyser[1] was installed in the Department of Electrical Engineering at the University of Alberta. Since, to date, there has been no work done to indicate how closely the measurements obtained from a Network Analyser study agree with the power system conditions which are being studied, there is considerable uncertainty among the Network Analyser users regarding such things as the proper correction to make for the resistance in the reactance coils, the effect of using a board autotransformer, and the magnitude of stray losses in the board. Because of these uncertainties a detailed knowledge of the Network Analyser accuracy would greatly aid the user. It is, therefore, the purpose of this thesis to determine the accuracy of the Network Analyser and to make recommendations which will aid the user in getting the most accurate results.

There are two methods of tackling this problem; one is to compare studies done on the Analyser with mathematical solutions of the same studies and the second method is to study the Network Analyser itself. The latter approach was chosen as it will give a broader, more general answer to

the problem. With this approach the problem may be broken down into three parts:

(a) Accuracy of system representation. This is a discussion of the equivalent circuits used on the Analyser to represent various parts of a power system.

(b) Accuracy of the Network Analyser components. This will include the measurement of stray capacitance and resistance values.

(c) Accuracy of instrumentation. This section will be concerned with the accuracy of the measuring desk instruments only.

In order to illustrate the conclusions and recommendations drawn from the study of the Analyser a sample load flow problem has been included.

CHAPTER II

SYSTEM REPRESENTATION

In order to ensure a clear meaning in this and following chapters, when the notation %N is used it will mean percent on the Network Analyser base. When % is used it will mean percent on a base of the quantity being discussed.

1. Generators:

A generator may be represented as a constant voltage source with a series impedance. This representation does not give a constant voltage under varying loads as an actual generator with voltage regulator would under steady state conditions. Thus, for load flow studies on the Network Analyser, a generator is represented as a constant voltage source with no series impedance. The generator losses are not a part of the transmission picture so the omission is not going to affect the study under steady state conditions.

In fault and transient studies, however, where the regulator effect is too slow to consider, it is necessary to insert the generator impedance since it may have a large effect on the system.

The Network Analyser generator impedance units have

reactance decades only. Thus the ratio of $\frac{X}{R}$ is fixed by the Q of the reactance coils. The actual ratio of $\frac{X'_d}{R}$ may vary from 10 to 100,[3] thus the generator impedance $\frac{X}{R}$ ratio of 33 will be correct for a limited number of cases. For $\frac{X'_d}{R}$ ratios of less than 33 a resistance unit may be used in series with the generator impedance or an R-X unit having an $\frac{X}{R}$ ratio of 20 may be used if $\frac{X'_d}{R}$ is less than 20. If, on the other hand, the ratio $\frac{X'_d}{R}$ is greater than 33 the Network Analyser representation of the generator will be inaccurate in that the resistance will be too high.

2. Transformers:

A transformer may be represented by several different "equivalent" circuits with varying degrees of accuracy. The exact equivalent circuit (fig.1a) is not normally used since the approximate equivalent circuit (fig.1b) is much easier to use and does not introduce appreciable error. The error introduced in the approximate equivalent circuit is small because the voltage drop across r_1 and x_1 is small compared with the total voltage. A further simplification (fig.1c) is usually made for use on the Network Analyser. I_n is normally of the order of 2-4% of the full load current and the loss component is usually of the order of 10% of the

reactive component. Thus neglecting I_n in the Analyser representation of a transformer introduces errors in the P and Q losses of the system, which, as a percentage of the transformer rating, will range from 2-4% for Q and 0.2-0.4% for P.

The next thing which must be considered is the ratio of $\frac{X_e}{R_e}$. The Analyser reactance units have an $\frac{X}{R}$ ratio of approximately 20 and the generator reactance units (which may be used independently of the generators) have an $\frac{X}{R}$ ratio of 33. Thus if the ratio of $\frac{X_e}{R_e}$ is less than 33 the values may be set accurately on the Analyser. If, however, $\frac{X_e}{R_e}$ is greater than 33 the transformer representation will have an excess of resistance. Practical values of $\frac{X_e}{R_e}$ range from 10 to approximately 100 so in some cases the proper values may be set and in other cases they may not.

If a transformer has an off nominal turns ratio or has taps, an autotransformer may be used to set the difference in voltage. Since the autotransformer will have losses it will introduce error in the system representation. For this reason it is recommended practice to use autotransformers only when necessary to close a loop. In other cases the off nominal turns ratios or taps may be accounted for by

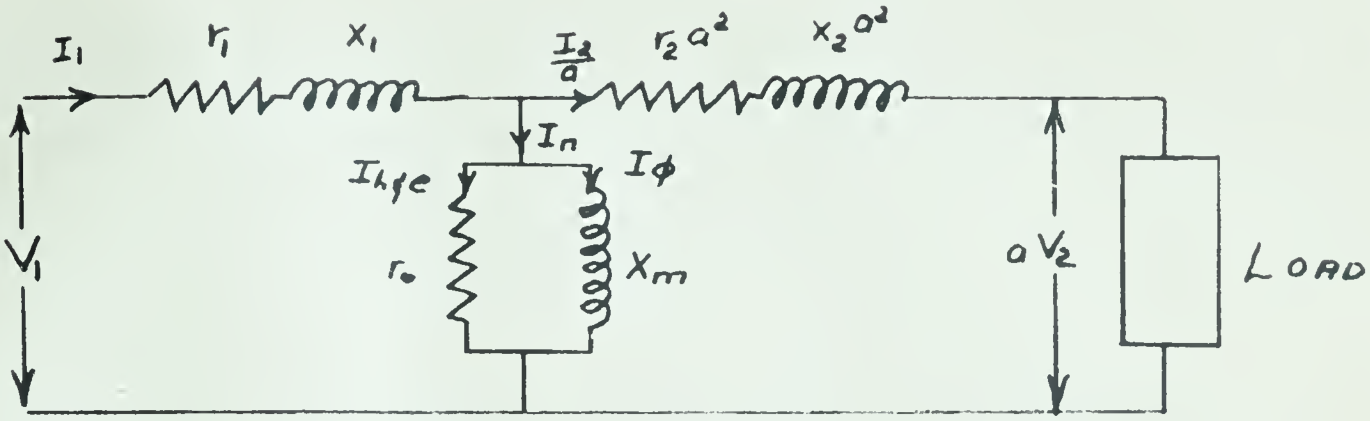


FIG. 1a TRANSFORMER EXACT EQUIVALENT CIRCUIT

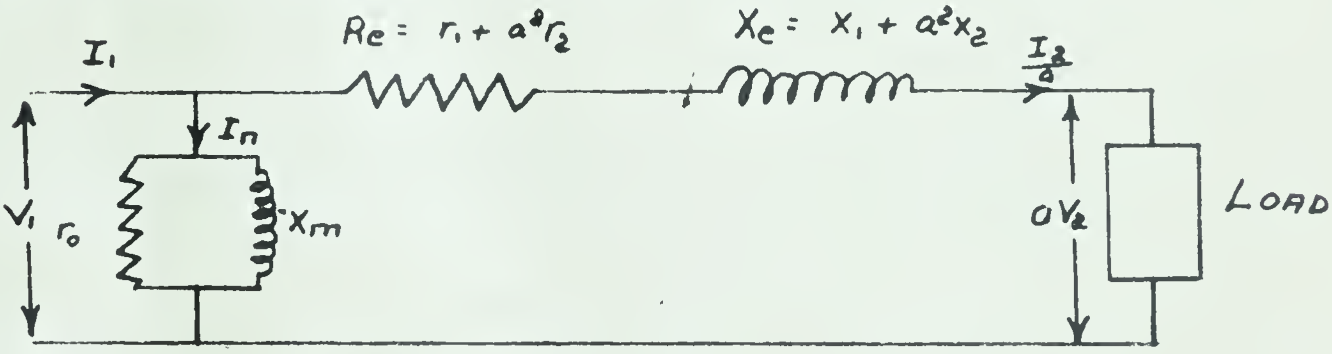


FIG. 1b TRANSFORMER APPROXIMATE EQUIVALENT CIRCUIT

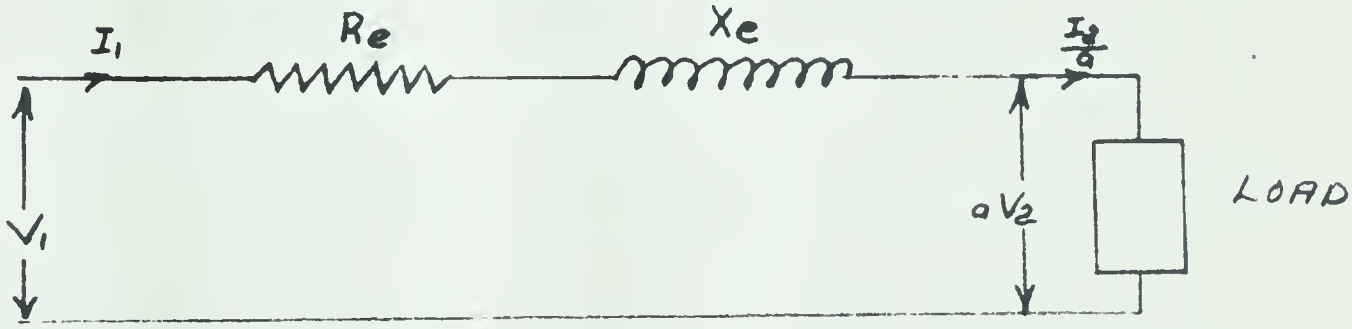


FIG. 1c TRANSFORMER EQUIVALENT CIRCUIT USED ON
THE NETWORK ANALYSER

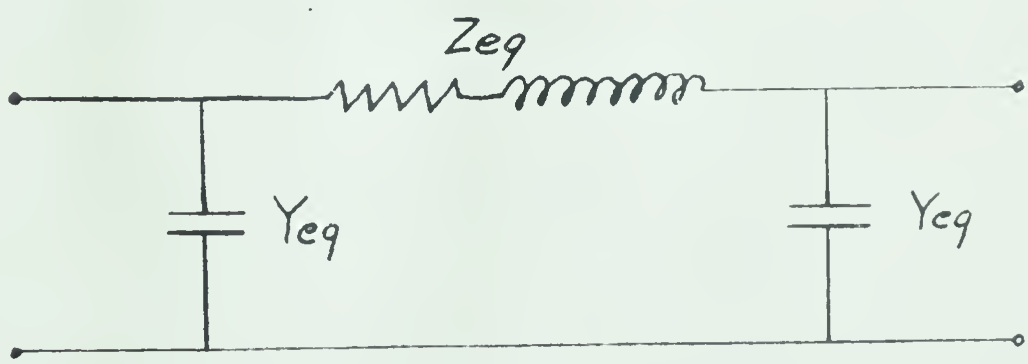


FIG 2 TRANSMISSION LINE EQUIVALENT π CIRCUIT

a change of base. The actual error introduced by the autotransformer will be discussed in the next chapter.

3. Transmission Lines:

There are several factors which must be considered when the equivalent circuit of a transmission line is being discussed.

The accuracy of the resistance, reactance and capacitance per mile must be considered. There are several factors such as the nature of the terrain and variation in sag which have small effects on the inductance and capacitance values and which cannot be readily calculated. The steel core in ACSR affects the resistance and inductance of a line and may cause them to change with current. The effect of the core can be calculated.[2] The resistance of a line is very dependent on temperature. For example a change from 0°C to 40°C will cause an increase of approximately 17% in the resistance of both copper and aluminum. Because of these factors the maximum accuracy obtainable for the line constants is approximately ± 1%. In order to attain this accuracy for resistance the temperature must be known within ± 2°C.

The next thing to consider is the representation of a

distributed constant circuit by a lumped constant circuit. The normal representation is the equivalent π circuit (fig.2). Since the current is a function of the distance from the end of the line the π circuit formed by multiplying the impedance per unit length by the length will have appreciable error for physically long lines. By analysis of the exact solution of the transmission line as given by the ABCD constants the exact equivalent π may be found such that

$$Z_{eq} = B$$

$$Y_{eq} = \frac{A-1}{B}$$

Since A and B are hyperbolic functions they may be expressed by infinite series which may be reduced to a few terms depending on the error which may be tolerated. A complete discussion of this method of determining the equivalent π may be found in the "Westinghouse Transmission and Distribution Book", Chapter 9. Thus a transmission line may be represented by an equivalent π, limited in accuracy only by the per mile values of resistance, reactance and capacitance.

4. Loads:

On the Network Analyser the loads are set using the measuring desk instruments so that the loads will not be

dependent on the accuracy of the components but will depend on the accuracy of the measurements only.

The fact that the loads are purely static loads rather than a combination of static and motor loads has no effect on load flow studies.

CHAPTER III

NETWORK ANALYSER COMPONENTS

In order to determine the absolute values of resistance, inductance and capacitance of the Analyser units, various bridge circuits* were used which were independent of the other Analyser components and of the measuring desk instruments. The bridges were arranged to allow control of the current flowing in the Network Analyser units so that the effect of current could be determined. A number of units were checked at varying currents and the variation of resistance, inductance and capacitance with current was found to be negligible. Thus the resistance and reactance units were measured with a current in the range of 50-100%N, the capacitance units were checked with a voltage of 50-100%N and the transformers were checked with 100%N voltage across them.

Only one setting per dial (in some cases more) was measured since the object was to get an overall picture of the accuracy of the units rather than to calibrate the units. The results of the measurements on the Network Analyser components are tabulated in tables I-V**

The manufacturer's description of the Network Analyser

* Appendix II
**Values measured between plugs

units will be found in Appendix III.

1. Resistance Units:

The R-X units in most cases have a zero resistance ranging from 0.02-0.06%N. This is subject to considerable unpredictable variation since there are sixteen contacts in series with each unit and the contact resistance may cause an increase of 0.1-0.2%N. This abnormally high zero resistance occured in two of the units tested and was eliminated by switching the contacts several times. Since the zero resistance is dependent on contact resistance the zero resistance for a given unit will vary over a normal range from 0.02-0.06%N while random cases may be as high as 0.2%N.

Because of this zero resistance the actual % error in the low %N values of the resistance decades is high, for example in the 10x1 decade the error is less than 1% or 0.1%N but in the 10x0.1%N decade the %N error is approximately the same so the actual % error is in the order of 5-10%. As the %N goes down then the actual % error will go up. For the 100%N values and over the error is generally less than 0.5%.

The inductance of the resistance units is small. For the 10x10%N setting it is approximately 0.16%N and goes down to 0.03%N for the 1x10%N setting. On the 10x1 setting it is approximately 0.06%N and decreases to 0.02%N at the 1x1%N setting. The x0.1%N decade has an inductance of approximately 0.01%N. Since the % of X in a circuit is usually, in practice, much larger than the % of R the stray reactance in the resistance units will have a very small effect on the total reactance.

2. Reactance Units:

The zero resistance error also shows up markedly in the apparent Q of the X units. At 100%N on the X units the % of R inherent in the coils is in the range from 4.8-5.3% of X, but at 10%N on the X units this has increased to 5.0-6.0% of X and at 1%N on the X units has increased to 12-14% of X. For the high %N X units the %N of R is in the range 4.8-5.5% of X. The generator reactances exhibit the same change in apparent Q. On the 10x10%N and the 5x100%N ranges the %N R varies from 3.0-3.2% of X, on the 10x1%N setting the %N R varies from 3.6-3.8% of X and on the 10x0.1%N setting the %N R is approximately 14% of X.

The actual %N values of reactance are quite consistent being less than 1% in error on the high ranges and less than 2% in error on the low ranges.

3. Capacitances:

The capacitance units have a zero capacitance error due to their stray capacitance to ground. The error is 0.04%N and has the same effect as the zero error in the resistance units in that the low %N values have a high % error. Above 5%N the error is within 1% but below 5%N the error increases rapidly to 40% at 0.1%N.

The other units of the Network Analyser also have a capacitance to ground. This capacitance was measured for approximately 50% of the units so that an average value could be calculated for each type of unit.

In the 200 and 400* series the units may be open circuited (both R and X) so a value of stray capacitance was found for both the brown end and the yellow end. (The two ends of each unit are distinguished by the color of the plug, either brown or yellow). When R and X are connected the stray capacitance measured at either end is equal to the sum of the capacitances measured at the yellow and brown ends

*Appendix III

when R and X were open. The capacitance was found to be independent of the R and X settings.

The ratio of brown end capacitance to yellow end capacitance is approximately equal for the 200 and 400 series units. The 600 series units have the same basic construction but do not have an open circuit position so that only the total capacitance could be measured. If the capacitance at each end were required an approximate result could be obtained by using the ratio of capacitances of the 200 and 400 series units.

The stray capacitances of each type of unit have been averaged and are as follows:

200 series units----yellow end----0.05%N
brown end-----0.035%N
400 series units----yellow end----0.05%N
brown end-----0.035%N
600 series units----0.10%N

900 series units----0.05%N

000 series units (generator impedances)----0.15%N

unmetered jumpers------0.03%N

4. Autotransformers and Coupling Transformers:

The autotransformer no load reactive losses range from 0.2%N capacitive to 0.3%N inductive and the power losses range from 1.0-1.5%N for 100%N voltage. These losses will

not represent the no load losses of the actual transformer since the power loss is too high and the reactive loss too low. Thus the no load losses of the autotransformers introduce error.

The tap settings on the autotransformers are a combination of 10%N taps on the main winding plus a 10x1%N boosting winding. Thus the taps below 100%N are set by reducing the voltage to the nearest 10%N below and then raising the voltage. using the boosting winding, to the desired value. This, coupled with the fact that the resistance and in most cases the reactance of the boosting winding is lower than that of the corresponding %N of the main winding, causes the impedance for a given %N below 100%N to be higher than for the corresponding %N above 100%N. The short circuit impedance for one transformer is plotted against tap setting in graph #1. The maximum short circuit impedance is approximately 0.5%N resistance and 0.3%N reactance. The resistance value does not vary appreciably with different transformers but the reactance has a wide variation as can be seen in Table V.

The coupling transformers have a no load reactive loss ranging from 0.3%N inductive to 0.9%N capacitive and a no load power loss of 0.4-0.9%N at 100%N voltage. The short circuit impedance has a resistance component ranging from 0.24-0.56%N

while the reactive component is constant at 0.1%N except for two units.

The values given for %N reactance and %N admittance are for a frequency of 500 cycles/second. The frequency error will have a direct bearing on the accuracy of these since they are both directly proportional to frequency. Thus a +1% error in frequency would cause a +1% error in reactance and a +1% error in admittance. The frequency determined at the time of testing was 498 cycles/second or an error of -0.4%. The frequency is controlled by an L-C circuit which will have a certain drift with time. This, then, introduces added error to the reactance and admittance values above the error in the units themselves.

TABLE I Actual %N of the Resistance Units

Setting Unit No.	0	10x0.1	10x1	10x10
		%N Resistance		
201	0.02	1.06	10.05	100.03
203	0.02	1.04	10.04	100.02
205	0.02	1.06	10.02	99.98
207	0.02	1.04	10.00	99.95
209	0.02	1.04	10.04	99.90
211	0.02	1.04	10.06	100.06
213	0.02	1.04	10.04	99.99
215	0.03	1.06	10.05	99.93
217	0.02	1.04	10.02	99.84
219	0.06	1.06	10.08	100.00
221	0.04	1.04	10.04	99.94
223	0.12	1.14	10.13	100.02
249	0.02	1.06	10.02	99.95
251	0.03	1.06	10.01	100.00
253	0.02	1.06	10.02	100.02
255	0.04	1.06	10.03	99.94
257	0.04	1.06	10.05	99.90
259	0.04	1.08	10.03	100.00
261	0.04	1.06	10.04	100.05
263	0.02	1.06	10.02	99.80
265	0.04	1.06	10.02	99.90
267	0.04	1.06	10.02	100.00
269	0.04	1.04	10.00	99.96
271	0.06	1.08	10.03	99.84
275	0.02	1.06	10.00	99.82
279	0.02	1.06	10.00	100.01
283	0.04	1.07	10.03	99.84
287	0.04	1.06	10.04	100.16
291	0.02	1.06	10.01	99.97
295	0.02	1.06	10.02	99.92

TABLE I (cont.)

Setting Unit No.	%N Resistance 0	10x0.1	10x1	10x10
401	0.02	1.04	10.00	99.90
405	0.02	1.04	10.02	99.92
409	0.02	1.04	10.00	99.98
413	0.02	1.05	10.02	99.84
417	0.02	1.05	10.02	99.93
421	0.04	1.06	10.02	99.96
449	0.02	1.06	10.03	99.92
453	0.02	1.05	10.04	100.06
457	0.03	1.05	10.03	99.86
461	0.03	1.05	10.04	99.78
465	0.02	1.04	10.04	99.94
469	0.02	1.05	10.02	99.90
473	0.03	1.04	10.03	100.09
477	0.03	1.05	10.05	99.91
481	0.04	1.05	10.05	99.89
485	0.04	1.04	10.04	99.90
489	0.04	1.06	10.05	99.86
493	0.04	1.06	10.04	99.94

TABLE I (cont.)

Setting Unit No.	%N Resistance 0	10x.1	10x1	10x10	5x100	10x100	2x1000
601	0.02	1.04	10.00	99.96	499.7		
603	0.02	1.05	10.03	99.90	499.4		
605	0.06	1.08	10.10	99.90	501.0		
607	0.02	1.06	10.02	99.86	499.4		
609	0.03	1.06	10.05	99.92	499.1		
611	0.04	1.06	10.04	99.96	499.0		
613	0.04	1.06	10.03	99.88	499.2		
615	0.04	1.06	10.05	99.88	499.8		
617	0.06	1.08	10.06	100.00	500.6		
619	0.03	1.05	10.00	99.95	496.5		
621	0.04	1.09	10.03	99.92	499.3		
623	0.03	1.04	10.00	99.88	499.4		
649	0.02	1.03	10.01	99.89	500.7		
651	0.02	1.06	10.02	99.95	499.9		
653	0.04	1.06	10.02	99.92	499.2		
655	0.02	1.04	10.01	99.87	499.5		
657	0.03	1.05	10.02	100.06	500.1		
659	0.02	1.04	10.00	99.91	499.5		
661	0.02	1.05	10.05	100.09	501.0		
663	0.04	1.05	10.17	99.93	501.9		
665	0.03	1.04	10.02	100.02	499.1		
667	0.03	1.04	10.02	100.01	499.0		
669	0.03	1.03	10.01	99.70	498.2		
671	0.03	1.04	10.04	99.92	499.4		
673	0.02		10.04	99.88		1003.8	2006.8
675	0.03		10.05	99.86		1001.8	2001.4
677	0.02		10.04	100.06		1003.6	2001.6
679	0.02		10.04	99.93		1003.4	2003.2
681	0.03		10.05	100.10		1006.2	1999.8
683	0.02		10.04	99.90		1000.2	2001.4
685	0.03		10.05	99.85		1004.4	2001.6
687	0.04		10.05	100.38		1006.0	2002.2
689	0.04		10.06	99.90		1004.0	2002.2
691	0.03		10.04	99.96		1004.9	1999.8
693	0.02		10.04	99.93		1004.9	2008.8
695	0.04		10.04	99.89		1003.8	2001.6

TABLE II Actual %N of the Reactance Units with Inherent Coil Resistance in %N

Setting Unit No.	%N Reactance 10x10 X	R	1x10 X	R	%N Resistance 10x1 X	R	10x0.1 X	R
201	100.0	5.10	9.95	0.51	9.95	0.56	1.00	0.12
203	100.0	5.00	9.90	0.52	9.92	0.58	1.01	0.12
205	99.7	5.00	9.92	0.52	9.91	0.59	1.00	0.12
207	99.7	4.92	9.93	0.49	9.92	0.56	1.00	0.12
209	100.0	4.94	9.92	0.50	9.92	0.56	1.02	0.10
211	99.9	4.96	9.92	0.50	9.95	0.56	1.01	0.12
213	99.9	5.00	9.97	0.50	9.85	0.56	1.02	0.12
215	100.0	4.92	9.92	0.50	9.90	0.56	1.00	0.12
217	99.9	5.00	9.91	0.48	9.97	0.56	1.02	0.12
219	99.2	5.00	9.92	0.50	9.90	0.58	1.02	0.14
221	99.7	4.92	9.91	0.50	9.92	0.58	1.02	0.12
223	100.3	5.18	9.93	0.62	9.90	0.65	1.00	0.20
249	99.5	5.00	9.93	0.52	9.83	0.56	1.02	0.12
251	99.3	4.90	9.91	0.52	9.95	0.56	1.01	0.12
253	100.0	4.84	9.97	0.50	9.93	0.56	1.01	0.12
255	100.2	5.12	10.00	0.52	9.88	0.58	1.03	0.14
257	100.2	5.24	9.93	0.54	9.93	0.56	1.02	0.12
259	99.7	5.20	9.93	0.54	9.91	0.58	1.03	0.14
261	100.0	5.00	9.92	0.52	9.95	0.58	1.03	0.12
263	99.3	5.04	9.92	0.54	9.88	0.58	1.01	0.12
265	99.9	4.98	9.92	0.52	9.83	0.58	1.02	0.14
267	100.5	4.96	9.93	0.50	9.83	0.58	1.02	0.12
269	100.0	5.00	9.92	0.50	9.90	0.58	1.01	0.10
271	100.0	4.96	9.92	0.52	9.92	0.58	1.01	0.14
275	99.3	4.88	9.91	0.48	9.90	0.58	1.02	0.12
279	100.0	4.96	9.95	0.50	9.92	0.56	1.02	0.12
283	100.2	5.04	9.93	0.52	9.92	0.56	1.02	0.12
287	99.9	5.06	9.93	0.50	9.86	0.54	1.00	0.12
291	100.2	5.10	9.99	0.52	9.93	0.58	1.01	0.12
295	100.5	4.94	9.92	0.52	9.92	0.56	1.01	0.12

TABLE II (cont.)

Setting Unit No.	%N Reactance 10x10 X	R	1x10 X	R	%N Resistance 10x1 X	R	10x0.1 X	R
401	99.5	4.94	9.91	0.50	9.83	0.54	1.02	0.10
405	100.2	4.96	9.91	0.50	9.80	0.56	1.01	0.12
409	100.2	5.02	9.95	0.50	9.92	0.56	1.00	0.12
413	100.3	4.82	9.93	0.50	9.86	0.56	1.01	0.12
417	99.5	4.94	9.91	0.50	9.82	0.56	1.00	0.12
421	100.2	4.98	9.91	0.52	9.93	0.58	1.01	0.12
449	99.7	4.98	9.91	0.50	9.91	0.54	1.02	0.12
453	99.9	5.00	9.95	0.50	9.93	0.56	1.00	0.10
457	99.2	5.00	9.90	0.50	9.88	0.56	1.01	0.12
461	100.2	5.00	9.93	0.50	9.92	0.58	1.00	0.12
465	99.9	4.98	9.92	0.50	9.86	0.56	1.01	0.12
469	100.0	5.02	9.95	0.52	9.76	0.58	1.01	0.12
473	99.9	4.94	9.91	0.50	9.86	0.60	1.02	0.12
477	100.0	4.92	9.91	0.50	9.92	0.56	1.00	0.12
481	100.2	5.16	9.95	0.52	9.90	0.56	1.01	0.12
485	99.5	5.02	9.90	0.50	9.88	0.56	1.01	0.12
489	99.5	4.86	9.86	0.50	9.90	0.56	1.01	0.12
493	100.3	5.00	9.93	0.50	9.88	0.56	1.00	0.12

TABLE II (cont.)

	%N Reactance				%N Resistance			
Setting	10x10		10x1		10x0.1		5x100	
Unit No.	X	R	X	R	X	R	X	R
601	99.5	5.14	9.94	0.58	1.02	0.12	492	24.3
603	99.7	5.22	9.94	0.56	1.02	0.12	494	24.7
605	100.3	5.30	9.90	0.58	1.02	0.12	496	24.8
607	99.0	5.04	9.94	0.56	1.01	0.12	495	24.3
609	99.9	5.12	9.90	0.60	1.02	0.12	493	24.2
611	99.9	5.18	9.88	0.60	1.00	0.12	492	24.2
613	100.0	5.20	9.92	0.58	1.02	0;14	495	24.9
615	101.2	5.10	9.78	0.58	1.02	0.14	296	24.3
617	100.2	5.08	9.94	0.60	1.02	0.14	494	24.6
619	99.5	5.12	9.90	0.58	1.01	0.12	495	24.3
621	99.7	5.20	9.82	0.60	1.02	0.14	495	24.4
623	99.7	5.16	9.92	0.54	1.01	0.12	495	24.5
649	100.3	5.06	9.94	0.60	1.01	0.12	492	24.3
651	99.7	5.14	9.87	0.60	1.01	0.12	496	24.7
653	99.3	5.18	9.88	0.58	1.00	0.12	493	24.3
655	99.7	5.20	9.87	0.58	1.02	0.12	495	24.6
657	99.3	5.22	9.94	0.58	1.01	0.12	495	24.5
659	99.7	5.12	9.90	0.58	1.02	0.12	495	24.3
661	100.2	5.20	9.78	0.60	1.02	0.12	496	24.4
663	99.9	5.24	9.80	0.58	1.02	0.12	495	24.4
665	99.1	5.14	9.94	0.58	1.00	0.12	495	24.5
667	100.3	5.22	9.87	0.56	1.01	0.12	496	24.6
669	99.5	5.14	9.95	0.58	1.02	0.12	492	24.2
671	100.0	5.22	9.95	0.56	1.01	0.12	494	24.5
Setting	10x10		10x1		2x1000		10x100	
673	99.5	5.20	9.87	0.56	2020	103	1003	54.0
675	100.2	5.10	9.87	0.56	2020	103	1003	52.9
677	99.5	5.20	9.80	0.54	2010	102	1002	52.8
679	100.0	5.06	9.80	0.56	2020	103	1003	53.1
681	99.5	5.22	9.82	0.58	2010	103	999	53.6
683	99.5	5.16	9.94	0.58	2030	103	1000	52.0
685	99.5	5.14	9.87	0.56	2020	103	1009	53.0
687	99.7	5.24	9.87	0.58	2020	103	1005	53.5
689	99.5	5.08	9.88	0.58	2020	102	1000	53.0
691	99.3	5.18	9.92	0.56	2010	103	1005	52.3
693	99.0	5.08	9.94	0.58	2030	102	1010	53.6
695	99.3	5.12	9.94	0.56	2000	102	1002	52.6

TABLE III Actual %N of the Generator Reactance Units with Inherent Coil Resistance in %N.

	%N Reactance				%N Resistance			
Setting	10x10		10x1		10x0.1		5x100	
Unit No.	X	R	X	R	X	R	X	R
003	100.2	3.10	9.90	0.36	1.00	0.12		
011	99.7	3.06	9.90	0.36	1.01	0.14		
019	99.1	3.06	9.90	0.36	1.01	0.14		
027	99.5	3.08	9.92	0.38	1.01	0.14		
035	100.0	3.14	9.94	0.38	1.02	0.14		
043	99.2	3.08	9.90	0.36	1.02	0.14		
051	99.3	3.36	9.90	0.58	1.01	0.36	499	16.1
059	99.2	3.08	9.90	0.38	1.01	0.14	500	15.9
067	99.9	3.06	9.82	0.36	1.02	0.14	502	15.6
075	99.2	3.06	9.90	0.36	1.01	0.14	502	15.9
083	99.5	3.12	9.95	0.38	1.02	0.14	500	15.8
091	100.0	3.08	9.87	0.38	1.01	0.16	502	15.7

TABLE IV Actual %N Admittance of the Capacitance Units

	%N Admittance								
Setting / Unit No.	5x10	1x10	10x1	5x1	1x1	10x0.1	5x0.1	1x0.1	0
301	49.8	10.0	10.0	5.07	1.04	1.04	0.54	0.14	0.04
303	49.8	10.0	10.0	5.04	1.04	1.03	0.53	0.14	0.04
305	49.8	10.0	10.0	5.07	1.03	1.03	0.53	0.14	0.04
307	49.6	10.0	10.1	5.09	1.04	1.04	0.54	0.14	0.04
309	49.8	10.0	10.0	5.04	1.04	1.04	0.54	0.14	0.04
311	50.1	10.0	10.0	5.01	1.04	1.04	0.54	0.14	0.04
313	50.0	10.0	10.1	5.06	1.04	1.04	0.54	0.14	0.04
315	50.0	10.0	10.1	5.07	1.03	1.03	0.53	0.14	0.04
317	49.8	10.0	10.1	5.07	1.03	1.03	0.53	0.14	0.04
319	49.6	10.0	10.1	5.07	1.04	1.04	0.54	0.14	0.04
321	49.7	10.0	10.0	5.05	1.04	1.03	0.54	0.14	0.04
323	49.8	10.0	10.0	5.04	1.04	1.03	0.53	0.14	0.04
349	49.6	10.0	10.1	5.07	1.04	1.04	0.54	0.14	0.04
351	49.8	10.0	10.0	5.04	1.03	1.03	0.53	0.14	0.03
353	49.9	10.0	10.0	5.04	1.04	1.04	0.54	0.14	0.04
355	49.8	10.0	10.0	5.05	1.03	1.03	0.53	0.14	0.04
357	50.1	10.0	10.0	5.02	1.04	1.03	0.54	0.14	0.04
359	49.8	10.0	10.0	5.04	1.03	1.03	0.53	0.14	0.04
361	49.8	10.0	10.0	5.04	1.03	1.04	0.54	0.14	0.04
363	49.9	10.0	10.0	5.04	1.04	1.03	0.53	0.14	0.04
365	49.9	10.0	10.1	5.04	1.04	1.04	0.54	0.14	0.04
367	49.9	10.1	10.0	5.02	1.03	1.04	0.54	0.14	0.04
369	49.8	10.0	10.1	5.05	1.04	1.03	0.54	0.14	0.04
371	49.8	10.0	10.0	5.05	1.03	1.03	0.53	0.14	0.04

TABLE IV (cont.)

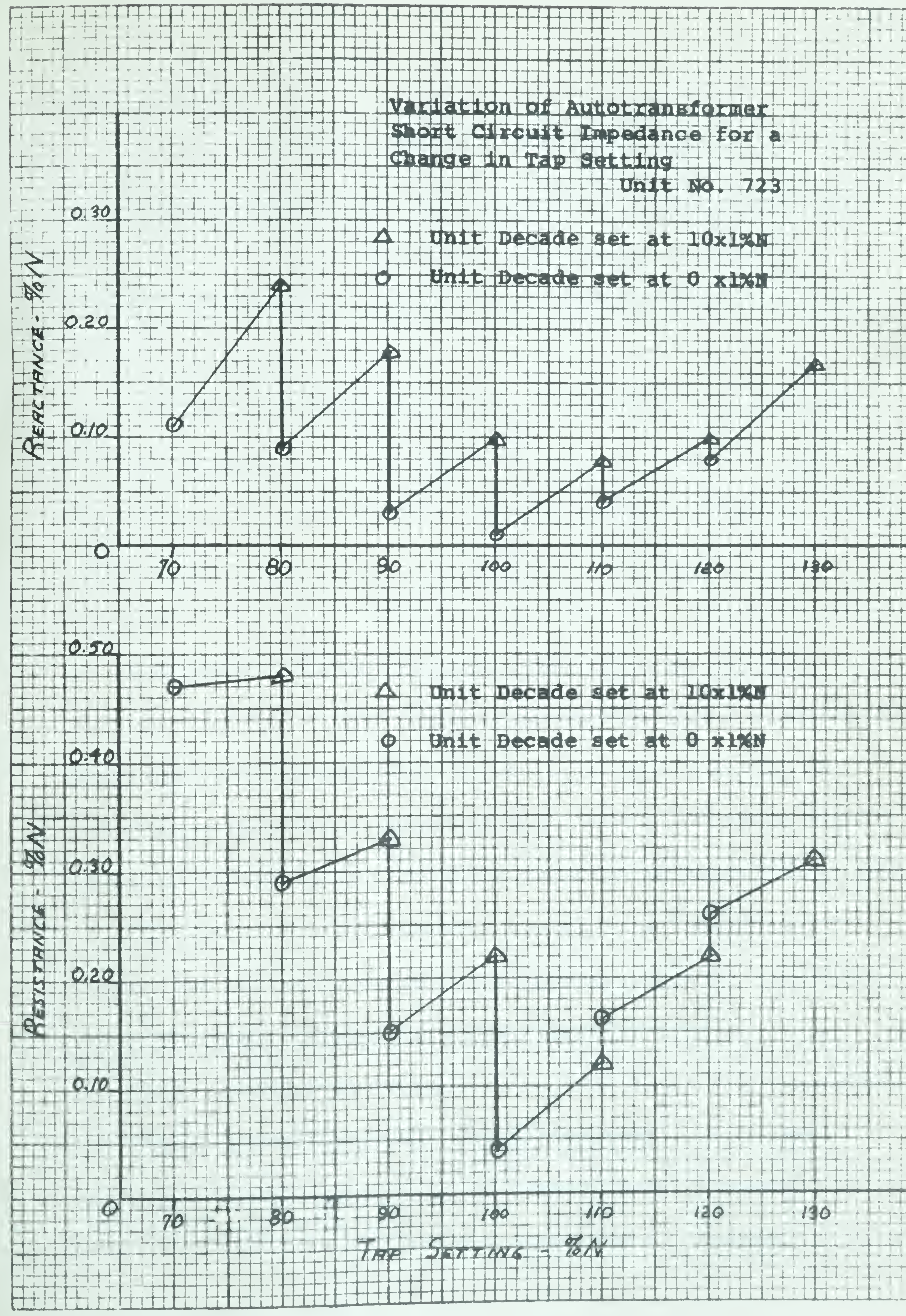
Setting / Unit No.	%N Admittances 10x10	5x10	10x1	5x1	1x1	10x0.1	5x0.1	1x0.1	0
501	99.3	49.8	10.0	5.04	1.03	1.03	0.54	0.14	0.04
503	99.9	50.1	10.1	5.07	1.04	1.03	0.53	0.14	0.04
505	100.3	50.2	10.0	5.01	1.03	1.04	0.54	0.14	0.04
507	100.3	50.1	10.0	4.99	1.05	1.03	0.54	0.14	0.04
509	100.2	49.8	10.1	5.05	1.03	1.04	0.53	0.14	0.04
511	99.3	49.6	10.0	5.05	1.04	1.03	0.53	0.14	0.04
513	100.3	50.1	10.0	5.05	1.04	1.04	0.53	0.14	0.04
515	99.9	49.8	10.0	4.99	1.03	1.04	0.54	0.14	0.04
517	100.4	0.54	10.0	4.99	1.04	1.03	0.53	0.14	0.04
519	100.2	50.1	10.1	5.07	1.03	1.03	0.53	0.14	0.04
521	100.3	50.4	10.1	5.05	1.04	1.03	0.53	0.14	0.04
523	99.9	49.6	10.1	5.07	1.04	1.04	0.54	0.14	0.04
573	100.0	49.9	10.1	5.05	1.05	1.04	0.54	0.14	0.04
575	100.4	50.4	10.1	5.08	1.04	1.04	0.54	0.14	0.04
577	99.5	49.8	10.0	5.01	1.05	1.03	0.53	0.14	0.04
579	100.2	50.1	10.0	5.05	1.03	1.03	0.54	0.14	0.04
581	99.7	49.6	10.1	5.05	1.05	1.04	0.54	0.14	0.04
583	100.3	50.2	10.0	5.05	1.05	1.04	0.54	0.15	0.04
585	99.7	49.6	10.0	5.05	1.05	1.04	0.54	0.15	0.04
587	100.0	49.9	10.1	5.08	1.04	1.04	0.54	0.15	0.05
589	99.7	49.4	10.1	5.07	1.06	1.05	0.55	0.15	0.05
591	99.9	49.8	10.1	5.05	1.04	1.04	0.54	0.14	0.04
593	99.5	49.4	10.1	5.07	1.05	1.04	0.54	0.15	0.05
595	99.9	49.6	10.1	5.07	1.05	1.03	0.54	0.14	0.04

TABLE V Open Circuit and Short Circuit Impedances of Autotransformers and Coupling Transformers

Values in %N

	Open Circuit Impedance			Short Circuit Impedance			
		Series	Shunt	130%N tap		70%N tap	
Unit No.	R	X_L	B_C	R	X	R	X
701	7,200	200		0.29	0.1	0.45	0.2
703	6,600	900		0.31	0.2	0.45	0.1
705	8,600	600		0.31	0.1	0.45	0.2
707	6,600	1,200		0.31	0.1	0.45	0.2
709	8,800	700		0.31	0.1	0.45	0.2
711	6,400		0.16	0.31	0.0	0.45	0.2
713	8,800	1,200		0.31	0.1	0.45	0.3
715	6,600	1,200		0.31	0.1	0.45	0.1
717	7,800	2,200		0.31	0.1	0.45	0.3
719	8,800	2,100		0.31	0.1	0.43	0.1
721	8,800		0.11	0.31	0.1	0.47	0.3
723	8,800	1,500		0.31	0.2	0.47	0.1

				Short Circuit Impedance	
				R	X
801	11,200		0.27	0.29	0.3
803	23,000		0.36	0.27	0.1
805	10,800		0.36	0.29	0.1
807	12,000		0.79	0.31	0.1
809	28,000		0.63	0.29	0.1
811	23,600		0.85	0.29	0.1
813	11,500		0.24	0.59	0.1
815	13,140		0.27	0.41	0.1
817	12,400	600		0.41	0.1
819	11,840		0.09	0.57	0.1
821	11,940		0.05	0.41	0.1
823	9,900	4,200		0.39	0.0
825	12,800		0.19	0.39	0.1
827	13,200		0.30	0.47	0.1
829	15,000		0.02	0.47	0.1
831	14,200		0.30	0.39	0.1


Variation of Autotransformer Short Circuit Impedance for a Change in Tap Setting
Unit No. 723
Unit Decade set at 10x1%N
Unit Decade set at 0 x1%N
Reactance - %N
0.30
0.20
0.10
0
70
80
90
100
110
120
130
Unit Decade set at 10x1%N
Unit Decade set at 0 x1%N
Resistance - %N
0.50
0.40
0.30
0.20
0.10
0
70
80
90
100
110
120
130
Tap Setting - %N

CHAPTER IV

MEASURING DESK INSTRUMENT ACCURACY

The stated accuracy of the measuring desk instruments is $\pm$ 1% of full scale value for the V and I meters, $\pm$ 2% of full scale value for the P and Q meters and $\pm 1^\circ$ for the phase angle meter.

In order to check the absolute accuracy of the meters a known voltage was used with known R and X values. The measuring desk reference voltage was checked against a Weston 1/4% voltmeter and this reference voltage was used to calibrate the measuring desk voltmeter. The measuring desk voltmeter is calibrated at 100%N voltage so the tests on the metering were done using a 100%N voltage and varying R and X values. Experimentation showed that the V, I, P, and Q meters do indicate within their specified limits. It was noted that there is considerable difference in error on different ranges.

The ability of the meters to reproduce a reading for successive applications of the same input must be considered since this is important if a difference of readings is desired. The time element must be considered here since the amplifiers and the zero positions will drift with time. Using the calibration position and the off position of the components measuring switch as a check the error did not become noticeable

in either the 100% or 0% reading until approximately four hours had elapsed after calibration. The mechanical zero error when checked after seven hours had a maximum drift of 1% of full scale on one meter. The effect of drift having been determined a check on the ability of the meters to reproduce a given reading was made. This showed that, provided the calibration is correct, the V, I, P and Q meters can reproduce a reading within an accuracy of ± 0.1% of the full scale for a given scale. A change in scale may cause a change in reading in the order of the absolute accuracy of the meters.

The phase angle meter was checked by comparing the phase angles of voltage and current in a known load. The phase angle between V and I was checked for various voltage phase angles and was found to have an error within a range of ± 1°. Below 40% (regardless of multiplying factor) on the V or I meters the phase meter tended to drift causing an increase in error. Thus to minimize the error the phase angle meter should be used on a range to give above a 40% reading on the V or I meter.

As in the other meters the readings may be reproduced to a much greater accuracy than the absolute accuracy. The

angles were found to be reproduceable to $\pm$ 0.1°. With the calibration voltage on the phase angle meter the reading varied over a range of $\pm$ 0.1° but there was no consistent drift with time.

CHAPTER V

A. CONCLUSIONS

1. The manufacturer's specifications of accuracy are incorrect for low values of resistance and capacitance and for the Q of the reactance coils when set at low reactance values. This is due to the effects of contact resistance and stray capacitances in the board. The no load current in the autotransformers is, in most cases, higher than that specified by the manufacturer. The accuracy of the remainder of the units has been found to be within the manufacturer's specifications. The manufacturer's specifications for the measuring desk instruments have also been found to be correct.

2. The choice of MVA base is an important factor in obtaining accuracy in a study. If a base is chosen so that the ohms base is high, the %N resistances will be low and consequently the % error in the resistance settings will be high. If the base is chosen so that the μmhos base is high, the %N admittances will be low and the stray capacitances will cause a large % error in the admittances. Thus a compromise must be made to achieve optimum accuracy for both impedances and admittances.

3. Provided the following recommendations are observed the losses in a load flow study may be determined to within 1% of total generation by taking the sum of the generation minus the sum of the loads. This assumes an exact knowledge of system resistances. An example illustrating this is included in Appendix I.

4. The losses in a system may be computed to an accuracy of ± 2% by using the currents measured during a load flow study and the system resistances provided the system resistances are known exactly. Any error in the given values of resistances will cause added error in the calculated losses.

Since the system reactances are high compared to the resistances the load flow will be governed mainly by the reactances. Thus small errors in the resistances of the system caused by stray resistances and the inability to set transformer resistances accurately will have a negligible effect on load flow. The resistance errors may, however, have a large effect on the power losses of the system so that a more accurate value of system losses will be obtained by calculating the losses from the currents read in the study and the actual values of system resistances.

B. RECOMMENDATIONS

1. In order that the electronic circuits will have time to stabilize the Analyser should be allowed to warm up for at least one hour. After the warm up period the meter calibration should be checked and adjusted if necessary. It is not necessary to turn the amplifiers off to set the mechanical zeros. Instead they may be adjusted with the components measuring switch in the off position and the meter multiplying factors at x1. The calibration of the meters should be checked every two or three hours to minimize error due to amplifier and zero adjustment drift.

2. Autotransformers should not be used unless it is necessary to match voltages in a closed loop. If it is necessary to use an autotransformer the no load losses should be calculated for the particular autotransformer being used from the open circuit impedance given in table V and the voltage read in the study. The voltage applied to the transformer is important since the loss varies as the square of this voltage.

In most cases the reactance component of the short circuit impedance can be neglected but the resistance component, which may be found in graph #1, should be taken into account.

3. If a difference of readings is necessary both readings should be taken with the same meter multiplying factors since changing multiplying factors will change the error in a reading. The readings should also be taken as closely together in time as possible in order to minimize the error introduced by meter and generator drift.

4. For values of reactance above 10%N in the R-X units the resistance of the coils should be taken as 5% of X. Thus the setting of the associated resistance should be (R_{actual} - 5% of X)%N. For values of reactance below 10%N the resistance should be taken as 5% of X + 0.06%N so that the setting of the associated resistance should be (R_{actual} - 5% of X - 0.06)%N.

If the R-X units are to be used with X=0 the R setting for values below 5%N should be corrected for stray resistance by setting R = (R_{actual} - 0.05)%N.

The adjustment in resistance for low values will reduce the error due to stray resistances but exact compensation cannot be made since the resistance in the contacts is variable.

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APPENDIX I

SAMPLE LOAD FLOW STUDY

In order to illustrate the accuracy of the Analyser on a Load Flow study, a sample system (fig.3) was set up and a complete set of load flow readings were taken. (table VII)

The resistance values of the lines were set using a coil Q of 20 so that the actual R and X values set for a line having $R_1 + jX_1$ as the required %N values of R and X would be $R = (R_1 - \frac{X_1}{20})\%N$ and $X = X_1\%N$. The transformers were assumed to have a resistance of 5% of their reactance. This was corrected for the zero resistance error by adding 0.06%N resistance for those transformers having X_e equal to or less than 10%N.

The values of the circuit constants as given in Table VI are assumed to be the exact circuit constants of the actual system so that the accuracy of this study is dependent on the Network Analyser only and does not include inaccuracies in system representation.

For the generator outputs and load, line and transformer inputs the relationship between P,Q,V and I was checked by assuming P,Q and V correct and calculating I. Except for one lightly loaded line the difference between calculated and

measured I was less than 1%.

In order to evaluate the losses in the system, the currents were assumed correct and the loss for each transformer and each line was calculated. The sum of these losses is 16.1%N and the sum of the losses measured by subtracting output of each line or transformer from its input came to 16.5%N. The loss determined by summing generation and loads and finding the difference came to 14.9%N. This could have error due to a drift in the system since the generation was recorded at the beginning of the study and the loads were recorded at the end of the study. A later check of this showed that the difference was 15.1%N indicating that the generators do tend to drift during the course of a study.

On a base of generation the calculated losses equal 6.56%, the losses measured for each individual unit total 6.73% and the losses measured by subtracting the sum of the loads from the sum of the generation equal 6.17%.

As a further example the loads were dropped to approximately 40% of their original value and a complete set of results again taken (table VIII). Only two generators were used in this case since the load was so light. The smallest station which represents a hydro plant was taken off the line.

The losses calculated as above came to 2.8%N and the

losses measured in individual units and summed came to 2.3%N. In many units, however. the power loss was 0.1% of the full scale reading or less so that the difference between power in and power out could not be detected. The losses in the units for which this occurred make up most of the difference between calculated and measured values. The loss determined by summing generation and loads came to 2.2%N.

It should here be pointed out that the calculated losses are not exact but may be in error by approximately 2%. This is due to the fact that the currents can only be read to an accuracy in the order of ± 1%.

To show the effect of autotransformer no load losses an autotransformer was connected in the system at transformer T5. The autotransformer was set at 100%N voltage so that it would not change the load flow in the system. The voltage on the autotransformer was 109%N. From table V the no load loss can be computed and was found to be 1.65%N. Summing the generation and loads the difference or system loss had increased to 3.9%N for no increase in load. Subtracting the autotransformer no load loss the system loss becomes 2.25%N or 0.05%N greater than previously.

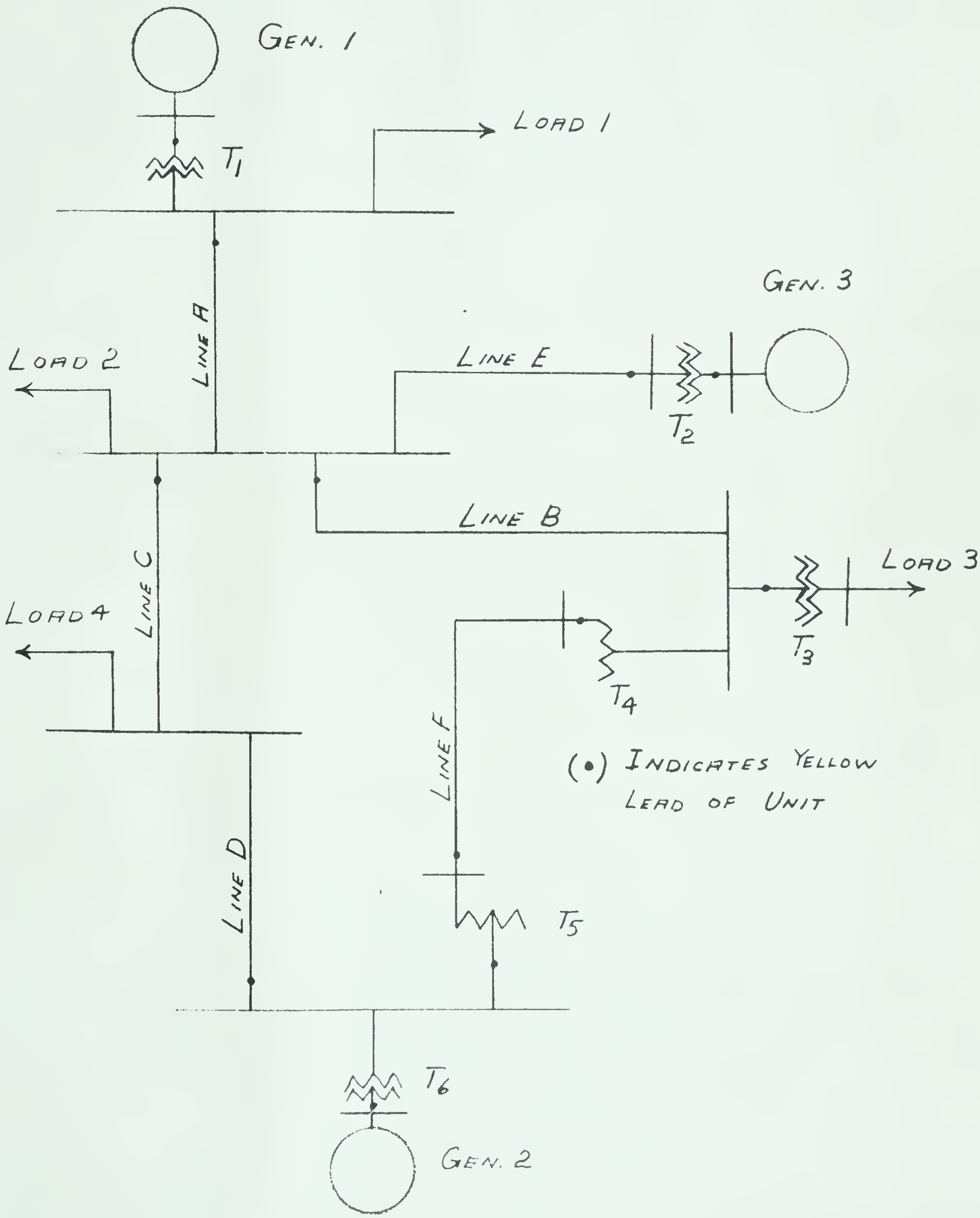


FIG. 3 SAMPLE LOAD FLOW STUDY

TABLE VI Unit Settings for Sample Load Flow Study

Values in %N using a 100MVA Base

Unit No.	System Circuit	Actual R + jX	Set R + jX	$\frac{Y}{2}$
203		10.5+j21.0	9.4+j21.0	
301	Line A			2.9
303				2.9
207		10.5+j21.0	9.4+j21.0	
305	Line B			2.9
307				2.9
211		10.5+j21.0	9.4+j21.0	
309	Line C			2.9
311				2.9
215		26.2+j52.4	23.6+j52.4	
313	Line D			5.7
315				5.7
219		5.25+j10.5	4.7+j10.5	
317	Line E			1.1
319				1.1
223		3.8+j22.7	2.7+j22.7	
321	Line F			21.2
323				21.2
201	T-1	0.90+j16.7	0.0+j16.7	
217	T-2	1.0+j20.0	0.0+j20.0	
221	T-3	0.31+j5.0	0.0+j5.0	
253	T-4	0.22+j3.3	0.0+j3.3	
257	T-5	0.22+j3.3	0.0+j3.3	
209	T-6	0.30+j4.7	0.0+j4.7	
		MW	MVAR	
101	Load 1	30	10	
105	Load 2	30	15	
109	Load 3	150	50	
117	Load 4	20	10	

TABLE VII   Readings for Full Load Study

	Yellow End				Brown End			
Lines	P	Q	V	I	P	Q	V	I
A	+30.5	- 1.0	102.0	29.8	- 29.4	- 3.2	98.2	30.0
	+30.5	+ 2.2	102.0	29.8	+29.5	+ 0.4	98.2	29.8
B	+48.0	0.0	98.2	48.5	- 45.5	- 0.5	93.0	48.5
	+48.0	+ 3.0	98.2	49.0	+ 45.5	- 2.0	93.0	49.0
C	-14.7	-10.7	98.2	18.3	+ 15.0	+ 5.4	101.5	15.6
	-14.7	- 7.8	98.1	16.8	- 15.0	- 8.5	101.4	16.8
D	+38.3	+ 8.0	116.6	33.4	- 35.0	-15.1	101.4	37.6
	+38.4	+16.0	116.6	35.8	+ 35.0	+ 9.0	101.4	35.8
E	+34.0	+ 1.4	100.8	33.8	- 33.1	- 1.5	98.2	33.8
	+34.0	+ 3.3	100.8	33.8	+ 33.4	+ 1.0	98.2	33.8
F	+111.0	+58.9	114.7	109.1	-104.0	-71.6	95.6	132.2
	+111.0	+86.5	114.6	122.9	+105.0	+52.9	95.6	122.9
Transformers								
T2	+34.1	+ 3.7	101.5	33.8	+ 34.0	+ 1.0	100.8	33.8
T1	+60.3	+15.8	104.3	60.0	+ 60.0	+ 9.8	101.9	60.0
T3	+150.0	+67.4	92.9	176.0	+149.0	+52.0	89.0	176.0
T4	+104.0	+71.8	95.5	132.6	+103.6	+66.0	92.9	132.6
T5	+111.5	+63.0	117.0	109.5	+111.2	+58.8	115.0	109.5
T6	+150.0	+79.9	120.0	141.9	+149.4	+70.2	116.6	141.9
Loads								
1	+30.0	+10.0	102.0	30.9				
2	+29.9	+15.0	98.3	33.6				
3	+148.8	+52.0	89.2	176.4				
4	+20.5	+10.3	101.6	22.2				
Generators								
1	+60.2	+15.8	104.3	60.0				
2	+149.8	+79.2	120.0	141.6				
3	+34.0	+ 3.2	101.3	33.5				

Note: The first row of readings for each line is read outside the capacitors and the second row for each line is read inside the capacitors.

TABLE VIII Readings for Light Load Study

	Yellow End				Brown End			
Lines	P	Q	V	I	P	Q	V	I
A	+20.2	-19.2	102.9	26.6	-19.6	+13.9	104.0	22.9
	+20.2	-15.8	102.9	24.6	+19.6	+17.2	104.0	24.6
B	+12.28	-14.49	104.0	18.2	-12.00	+8.60	105.0	14.0
	+12.30	-11.34	104.0	16.0	+12.05	+11.91	105.0	16.1
C	-5.15	-4.60	104.0	6.60	+5.16	-1.71	104.9	5.12
	-5.15	-1.47	104.0	5.10	+5.15	-1.59	104.9	5.10
D	+17.25	-5.90	109.0	16.72	-16.60	-6.02	104.9	16.86
	+17.28	+0.92	109.0	15.84	+16.62	-0.4	104.9	15.88
E	0.00	+0.32	104.2	0.23	0.00	-2.62	104.0	2.48
	0.00	+1.50	104.2	1.38	0.00	+1.43	104.0	1.30
F	+48.6	-15.0	109.0	46.5	-48.0	-29.3	106.0	53.0
	+48.7	+10.0	109.3	45.4	+48.0	+5.5	106.0	45.4
Transformers								
T1	+33.1	-8.9	101.5	33.9	+33.0	-10.7	102.9	33.9
T2	0.0	0.0						
T3	+60.0	+20.0	105.0	60.0	+60.0	+18.2	104.0	60.0
T4	+48.0	+29.0	106.0	53.0	+48.0	+28.0	105.0	53.0
T5	+48.7	-14.5	109.0	46.5	+48.7	-15.4	109.3	46.5
T6	+66.5	-19.0	108.3	63.1	+66.5	-21.0	109.0	63.1
Loads								
1	+13.10	+8.09	102.8	14.88				
2	+12.64	+7.88	104.0	14.24				
3	+60.0	+18.50	104.0	60.0				
4	+11.60	+7.75	104.8	13.22				
Generators								
1	+33.0	-9.0	101.4	33.9				
2	+66.5	-19.3	108.3	63.1				

Note: The first row of readings for each line is read outside the capacitors and the second row for each line is read inside the capacitors.

TABLE IX Comparison of Calculated and Measured Losses for a Sample Load Flow Study

Values in %N on a 100 MVA Base

	Full Load		Light Load	
Lines	Calculated	Measured	Calculated	Measured
A	0.93	1.0	0.635	0.6
B	2.52	2.5	0.269	0.25
C	0.30	0.3	0.027	0.0
D	3.36	3.4	0.656	0.66
E	0.60	0.6		
F	5.74	6.0	0.784	0.7
Transformers				
T1	0.32	0.3	0.103	0.1
T2	0.11	0.1		
T3	0.96	1.0	0.112	0.0
T4	0.39	0.4	0.062	0.0
T5	0.26	0.3	0.048	0.0
T6	0.60	0.6	0.12	0.0
Sum of Losses	16.09	16.5	2.826	2.31
Sum of Generation		244.0		99.5
Sum of Loads		229.1		97.3
Losses		14.9		2.2

With autotransformer for light load study:

Sum of Generation	101.3
Sum of Loads	97.4
Losses	3.9
Calculated Autotransformer Loss	1.65
Losses in System	2.25

APPENDIX II

BRIDGE CIRCUITS

1. Resistance:

A direct ratio bridge (fig.4) was used to measure the resistance units and the values were recorded directly in %N.

To measure the inductance of the resistance units an Owen Bridge[4] was used (fig.5). Assuming R_M has negligible inductance and C_N negligible resistance it can be shown that

$$R = \frac{C_N}{C_P} \cdot R_M$$

$$L_R = C_N R_M R_P$$

2. Inductance:

Two different bridge circuits were used to measure the inductance of the X units. The first (fig.6a) is a resonance bridge so it is frequency sensitive. Thus the frequency must be known accurately in order to use the results from the bridge.

The frequency was determined by finding the value of LxC for resonance using a standard inductance and capacitance. LxC was found to be 102.1×10^{-9} farads x henries and for 500 cycles/sec. LxC is $\frac{1}{\pi} \times 10^{-6} = 101.3 \times 10^{-9}$. From this the frequency may be calculated and comes to 498 cycles/sec.. L, in %N, is

$$\frac{2\pi \times 102.1 \times 10^{-9}}{C \times 10^{-6}} \times 100\%N = \frac{0.1021 \times 2\pi \times 100\%N}{C}.$$

The resistance is independent of frequency so that $R_L = R_S$.

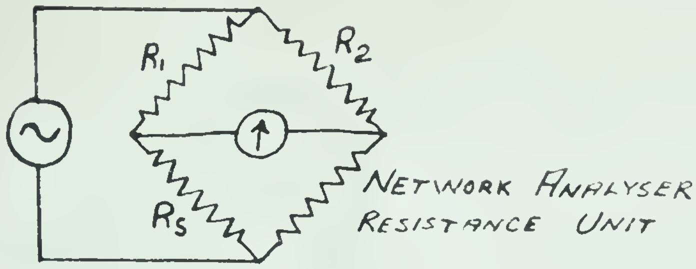
The second bridge (fig.6b) used for inductance measurements is a simple ratio bridge. The standard inductance used has a lower Q than the Network Analyser X units so it was necessary to add resistance in the X side of the bridge. Thus $L = L_S$ and $R_L = R_{LS} - R_S$.

3. Capacitance:

A direct ratio bridge (fig.7) was used for both the capacitance units and measuring the stray capacitances in the other units.

4. Transformers:

The transformer open circuit and short circuit impedances were measured using a direct ratio bridge as in fig. 8. The results were recorded directly as %N.



$R_1 = R_2$ FOR ALL RESISTANCE MEASUREMENTS

FIG. 4. RESISTANCE BRIDGE

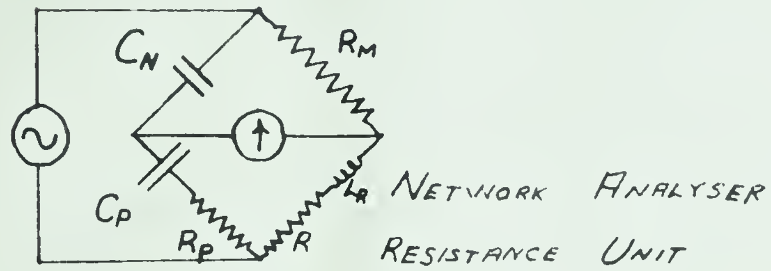
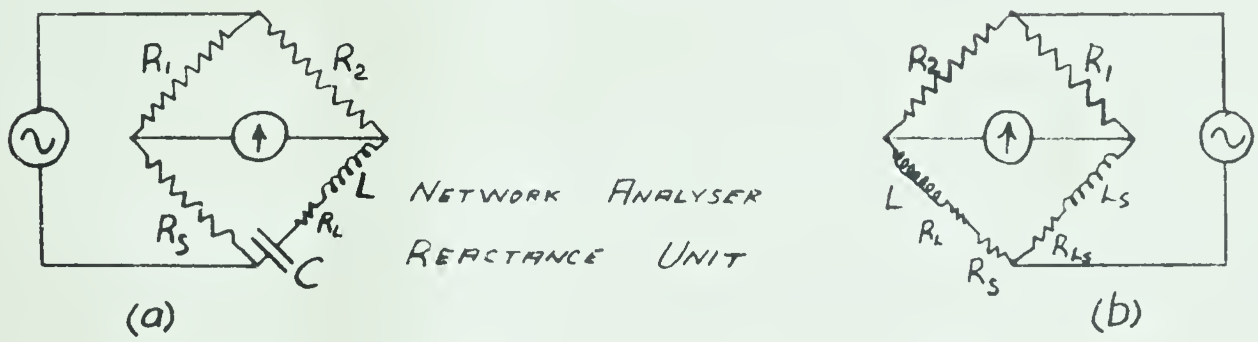


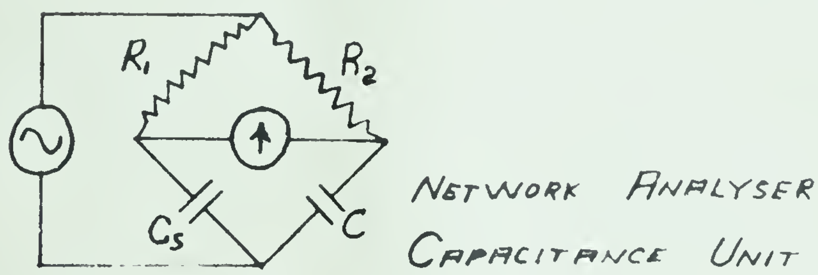
FIG. 5. OWEN BRIDGE



$R_1 = R_2$ FOR $X \geq 10\% N$

$R_1 = 10 R_2$ FOR $X < 10\% N$

FIG. 6. REACTANCE BRIDGES



$R_1 = R_2$ FOR ALL CAPACITANCE MEASUREMENTS

FIG. 7. CAPACITANCE BRIDGE

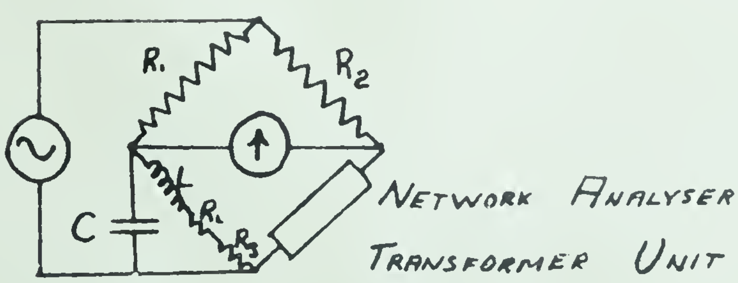


FIG. 8. IMPEDANCE BRIDGE

Unit	1st figure of 3 figured number	number of units in the N.A.	electrical value of R	electrical value of X	electrical value of C	transformer ratio	accuracy of elements in % of adjusted value	quality of coils $Q = \frac{X}{R_L}$	max. current	max. voltage	max. by-pass power of transformer	Remarks
Generator Unit	0	6	-	0 ÷ 122 %	-	-	X: ± 2	33,3 ± 3,3	1000 %	250 %	-	-
		6	-	0 ÷ 622 %	-	-	X: ± 2	33,3 ± 3,3	1000 %	250 %	-	-
Load Impedance Unit	1	24	20 ÷ 1620 %	20 ÷ 1620 %	-	output volt.= 70 ÷ 131 % of input volt.	R : ± 3 X : ± 3 Tr.ratio: ±0,5	20 ± 2	R,X: 600 % Transf.prim. curr. 600 %	R,X : 150 %	1500 %	no load curr.of trans. at 100% voltage: ≦ 3 % shortcircuit imped.of transformer: ≦ 1%
RX Line Unit	2,4	48	0 ÷ 122 %	0 ÷ 122 %	-	-	R : ± 1 X : ± 2	20 ± 1	R,X : 600 %	R,X : 150 %	-	-
	6	24	0 ÷ 622 %	0 ÷ 622 %	-	-	R : ± 1 X : ± 2	20 ± 1	R,X : 600 %	R,X : 150 %	-	numbers up to 671
		12	0 ÷ 3220 %	0 ÷ 3220 %	-	-	R : ± 1 X : ± 2	20 ± 2	R,X : 600 %	R,X : 150 %	-	numbers higher than 671
Capacitance Line Unit	3	24	-	-	0 ÷ 62,1 %	-	C : ± 1	-	-	C : 2000 %	-	-
	5	24	-	-	0 ÷ 122,1%	-	C : ± 1	-	-	C : 2000 %	-	-
Variable Voltage Transformer	7	12	-	-	-	output volt.= 70 ÷ 131 % of input volt.	Trans.ratio: ± 0,5	-	Transf.prim. current: 600 %	-	1500 %	no load curr. at 100 % volt: ≦ 1 % shortcircuit imped.: ≦ 0,5%
Coupling Transformer	8	10 (Nos.813÷831)	-	-	-	1 : 1	Trans.ratio: ± 0,5	-	Trans. prim. curr: 600 %	-	1500 %	no load curr. at 100 % volt: ≦ 1 % shortcircuit imped.: ≦ 0,5%
		3 (Nos.801,803,805)	-	-	-	1 : $\sqrt{3}$	Trans.ratio: ± 0,5	-	Trans. prim: curr: 600 %	-	1500 %	no load curr. at 100 % volt: ≦ 1 % shortcircuit imped.: ≦ 0,5%
		3 (Nos.807,809,811)	-	-	-	1 : 2	Trans.ratio ± 0,5	-	Trans. prim: curr: 600 %	-	1500 %	no load curr. at 100 % volt: ≦ 1 % shortcircuit imped.: ≦ 0,5%
Metered Jumper	9	24	-	-	-	-	-	-	-	-	-	mounted on the rear of the switchboard
Unmetered Jumper	-	12	-	-	-	-	-	-	-	-	-	mounted on the rear of the switchboard

The following quantities represent 100%N on the Analyser, that is they are the Network Analyser base values.

Voltage	15 volts
Current	30 ma
Effective power	0.45 watts
Reactive power	0.45 vars
Resistance	500 ohms
Capacitance	$\frac{2}{\pi} = 0.637\ \mu f$ (500 ohms at 500 cycles/sec.)
Inductance	$\frac{1}{2\pi} = 0.1592\ h$ (500 ohms at 500 cycles/sec.)